



Temperature-compensated and Density-independent Moisture Content Determination in Shelled Maize by Microwave Measurements

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(Received 15 December 1997; accepted in revised form 1 July 1998)

Moisture content of shelled maize, *Zea mays* L., was correlated with the attenuation and phase shift of electromagnetic waves travelling through a layer of grain. Several calibration equations are presented in the paper that are based on measurements taken at 15.2 GHz for various grain densities, moisture contents and temperatures. Validation of the calibration equations indicated that moisture content can be predicted with an uncertainty less than $\pm 0.72\%$ moisture content w.b. at the 95% confidence level. Moisture predictions are largely independent of bulk density variations at temperatures from 4 to 45°C and moisture contents from 9 to 19% w.b. By following one approach described, the grain bulk density can be determined from the same measurements with an uncertainty of less than 25 kg/m³. With another approach, the grain bulk density cannot be determined, but moisture content is determined independent of the material bulk density and compensated for temperature. No differences among three maize hybrids were observed in the measured data. © 1999 Silsoe Research Institute

Notation

- d layer thickness, cm
- e difference between predicted and reference values
- \bar{e} mean value of differences, bias
- g partial density of dry material, kg/m³
- i running index
- j complex operator ($=\sqrt{-1}$)
- k partial density of water in grain, kg/m³
- m mass, kg
- n integer
- r correlation coefficient
- v volume, m³

- A attenuation of microwave signal, decibels
- B numerical coefficient
- M moisture content, percent wet basis
- N number of samples
- P power, W
- T temperature, °C

Greek letters

- α attenuation constant
- β phase constant
- γ complex propagation constant
- δ phase angle of the transmission coefficient, deg
- ϵ^* relative complex permittivity
- ϵ' dielectric constant
- ϵ'' loss factor
- θ phase angle of the reflection coefficient, deg
- λ wavelength, cm
- ρ material density, kg/m³
- τ complex transmission coefficient
- ϕ phase shift, deg
- Δ combined-variable term
- Γ complex reflection coefficient
- ψ, Ψ, Φ functions

Subscripts

- d dry material
- i running index
- w water
- o free space value

1. Introduction

On-line moisture content monitoring is necessary for efficient control of many dynamic processes, and without it the processes cannot fully be automated. Monitoring of

material moisture content must be fast enough to allow automation response. It should also be continuous and preferably non-destructive to overcome process disturbances. It must also have sufficient accuracy to assure required control of the processes. For some time, a new branch of metrology, *microwave aquametry*,¹ has been developing, and its methods, based on microwave techniques, have proven to be successful in meeting these requirements.

Microwave methods of moisture content determination in grain have been studied for several years.²⁻⁴ The obtainable precision may well prove appropriate for continuous monitoring of moisture content in such processes as postharvest drying and cereal grain processing and also be independent of bulk density fluctuations. Furthermore, the bulk density of the flowing grain could be determined from the same measurements. The material temperature affects the measurement, and it must be taken into account during final calibration of a microwave instrument.

The method consists of measuring the attenuation and phase shift of a microwave beam passing through a layer of grain located between two antennas. The results of the measurement, together with the material temperature, are included in the calibration equation which provides the material moisture content and its bulk density.

Following the general line of research toward continuous and non-destructive on-line monitoring of moisture content in grain,⁴ this paper reports recent developments, mainly in temperature compensation and improving precision of the density-independent calibration equations. Experimental data presented in the paper relate to shelled maize, but the results are transferable to other kinds of grain,⁵ as well as other granular and powdered materials. Although static experiments are described in the paper, the technique should be applicable to dynamic measurements of flowing material.

2. General considerations

The definition of moisture content M in percent (wet basis) can be presented as

$$M = \frac{m_w}{m_w + m_d} \times 100 = 100\xi \quad (1)$$

where m_w is the mass of water, m_d is the mass of dry material, and ξ is the fractional moisture content determined on the wet basis. For a given volume of material, v , Eqn (1) may be rewritten in the form

$$\frac{M}{100} = \frac{m_w/v}{m_w/v + (m_d/v)} = \frac{k}{k + g} = \frac{k}{\rho}, \quad (2)$$

where k is the partial density of water and g is the partial density of dry material, with $k + g = \rho$, where ρ is the bulk density of the moist material. It might be noted that simple relationships exist, namely

$$k = \frac{m_w}{v} = \rho\xi \quad \text{and} \quad g = \frac{m_d}{v} = \rho(1 - \xi) \quad (3)$$

which will be used later.

The two commonly used parameters of an electromagnetic wave travelling through a layer of material are the magnitude and phase of the transmission coefficient expressed as

$$\tau = \frac{(1 - \Gamma^2)e^{-\gamma d}}{1 - \Gamma^2 e^{-2\gamma d}} = |\tau|e^{j\delta} \quad (4)$$

where $\Gamma = |\Gamma|e^{j\theta}$ is the complex reflection coefficient at the air-material interface, $|\tau|$ is the modulus of the transmission coefficient, δ is its phase angle and γ is the wave propagation constant, $\gamma = \alpha + j\beta$. The measure of the change in wave magnitude is called *the attenuation*, and is given as

$$A = 20 \log |\tau| = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}} \text{ (dB)} \quad (5)$$

where P_{in} and P_{out} are microwave power levels measured at the input and the output of the material layer. Phase delay in the material (also known as *phase shift*, if taken as a positive value) may be expressed in radians or degrees, and is usually defined as

$$\phi = \delta - 360n \text{ (deg)} \quad (6)$$

where n is an integer. It has been noted previously²⁻⁴ that both the attenuation and the phase shift are distinct functions of the grain moisture content, density, temperature, layer thickness and the wavelength. For a linearly polarized plane wave normally incident on the plane surface of a homogeneous layer of material of infinite extent (so diffraction effects at the edges can be neglected), the expression for the attenuation and phase shift as functions of the material dielectric properties can be written as

$$A \simeq 8.686 \pi \frac{d}{\lambda_0} \frac{\varepsilon''}{\sqrt{\varepsilon'}} \text{ (dB)} \quad (7)$$

$$\phi \simeq 360 \frac{d}{\lambda_0} (\sqrt{\varepsilon'} - 1) \text{ (deg)}$$

where A and ϕ are both taken as positive numbers, ε' is the dielectric constant, ε'' is the loss factor, d is the layer thickness and λ_0 is the free-space wavelength. Approximations in Eqn (7) are valid for $\varepsilon'^2 \gg \varepsilon''^2$, which is true for most cereal grains. At a given frequency, the material permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$ is a function of its moisture content, density and temperature.⁶

The observations can be expressed in a general form where the measured variables, A and ϕ , are each a function of the material parameters: moisture content M , density ρ and temperature T ,

$$A = \Phi_1(M, \rho, T) \quad \text{and} \quad \phi = \Phi_2(M, \rho, T) \quad (8)$$

The moisture content and density of the material can be expressed in terms of partial densities, k and g , according to the definitions presented in Eqns (2) and (3), and the measured variables can be redefined as

$$A = \psi_1(k, g, T) \quad \text{and} \quad \phi = \psi_2(k, g, T) \quad (9)$$

These two equations can be solved to express the partial densities of water and dry material in terms of measured variables:

$$k = \Psi_1(A, \phi, T) \quad \text{and} \quad g = \Psi_2(A, \phi, T) \quad (10)$$

Thus, the moisture content can be expressed as

$$M = \frac{\Psi_1(A, \phi, T) \times 100}{\Psi_1(A, \phi, T) + \Psi_2(A, \phi, T)} \quad (11)$$

which contains only the measured wave variables, A and ϕ , and temperature T , determined experimentally. Also, the density of the wet material

$$\rho = \Psi_1(A, \phi, T) + \Psi_2(A, \phi, T) \quad (12)$$

can be determined at the same time. Thus, the density of wet material need no longer be considered a disturbing factor in the moisture content measurement, because it can be determined during this measurement and used for other purposes. Uncertainty of calibration determines the uncertainty of the density determination and the moisture content determination, and it generally depends on two factors—the uncertainty in measuring values of variables A and ϕ , as well as T , and the nature of the functions chosen for approximation of the relationship expressed in Eqn (9).

The defining process in determining the relationships (11) and (12) is called the calibration of the measuring system. Any calibration procedure must include the solution of two basic problems: choice of the structure of the mathematical models of the physical relations (8), and estimation of the parameters (numerical coefficients) for these models. Several simple models are considered in the paper. More complex models could contain equations of a second or third order, as well as multivariable terms. Solving those equations for M and ρ might require elaborate computations, but the general procedure is similar to that described above.

3. Materials and methods

The measurement arrangement is shown in *Fig. 1*. It consists of two rectangular waveguide (WR-62, IEC-R

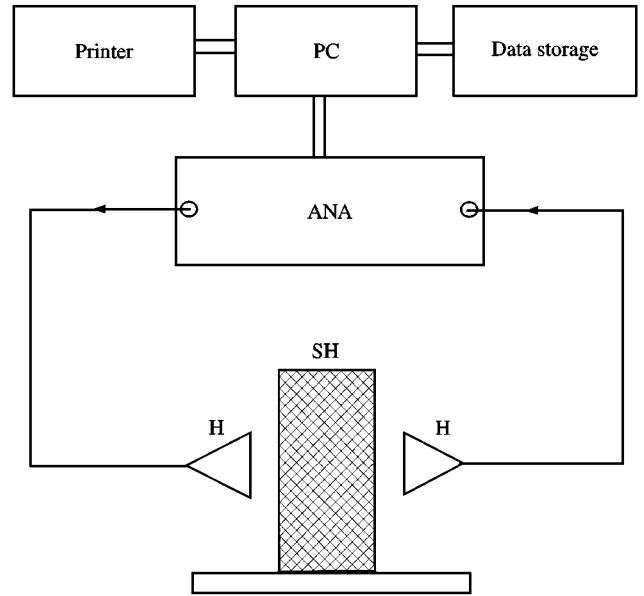


Fig. 1. Diagram of the measuring system. ANA—automatic network analyzer; H—horn antenna; PC—personal computer; SH—sample holder (Styrofoam box)

140 or British WG-18, inside dimensions 1.58 by 0.79 cm) horn antennas, connected to the two ports of a vector network analyzer through waveguide-to-coaxial adapters and coaxial cables. The network analyzer was calibrated in the transmission mode and the measurements were automated with a computer program written for this purpose. A container, constructed from 2.5 cm thick Styrofoam panel with 15.2 by 15.2 cm rectangular cross-section, was filled with maize kernels and located between the antennas (aperture dimensions 5 cm by 3.7 cm), which were 10.4 cm apart. In this way, the sample of grain was exposed to the incident wave as a layer of material of uniform thickness, and the Styrofoam has electrical properties so close to those of air that it does not interfere with the measurements. A sample thickness of 5.2 cm was selected so that a 10 dB minimum-attenuation criterion⁶ was met to avoid multiple reflection problems for all moisture content levels, densities and temperatures. The operating frequency of 15.2 GHz corresponds to the best impedance matching of the two antennas with the empty container between them.

Shelled samples of three yellow-dent maize, *Zea mays* L., hybrids (FR618 × LH123, FR618 × FR600 and FR1064 × LH59), grown in 1993 in Illinois and dried with natural airflow to 14% w.b. moisture content, were used for the measurements. Three-litre maize samples of different moisture contents were prepared and stored in sealed jars at 4°C to equilibrate. When necessary, moisture was added by spraying distilled water on the maize

kernels before sealing samples. To obtain a uniform moisture content throughout the entire sample, each sample was mixed periodically by rotating the sealed jar. Before the microwave measurements were performed, the sealed samples were allowed to equilibrate to room temperature ($24 \pm 1^\circ\text{C}$) for at least 24 h. For each sample, the maize kernels were poured into the container, which was weighed and then placed between the antennas, and the attenuation and phase shift of the electromagnetic waves were measured. The measurements were repeated for the same sample at gradually increased densities obtained by settling the grain in the container and adding more kernels to fill the container. Immediately after the microwave measurements, the moisture content of each sample was determined by drying duplicate 15 g samples of whole-kernel maize in a forced-air oven at 103°C for 72 h.⁷ To prepare samples for the next series of microwave measurements, they were permitted to dry under ambient conditions until they reached the desired moisture contents. The samples were then returned to the jars, sealed and held for at least 3 days at 4°C to equilibrate, and the procedure was repeated for each subsequent measurement.

The microwave measurements were also carried out for material temperatures below and above the room temperature (24°C). Samples of various moisture contents were allowed to stabilize for 3 days in a chamber where the temperature was adjusted to 4, 14, 34, or 45°C . Because of the excellent insulating characteristics of the Styrofoam container and the short time interval required for the measurements, grain temperatures in the region sensed by the microwave beam did not vary more than 1°C during the measurements, as checked with a mercury thermometer before and after measurements. The same procedure used at 24°C was repeated at each temperature. Overall, 518 microwave measurements were carried out for samples of various moisture contents and densities at five different temperatures.

4. Experimental results

Measurements of attenuation and phase shift, obtained for the three maize hybrids at three temperatures, are shown in Fig. 2 as a function of moisture content. Similar results for three moisture content levels are shown as a function of grain temperature in Fig. 3, and as a function of bulk density in Fig. 4. No differences between measured data for the three hybrids were detected.

To develop the calibration equations for moisture content determination from the measured microwave parameters, the whole set of experimental data, containing points for all moisture contents from 9 to 19% w.b. and

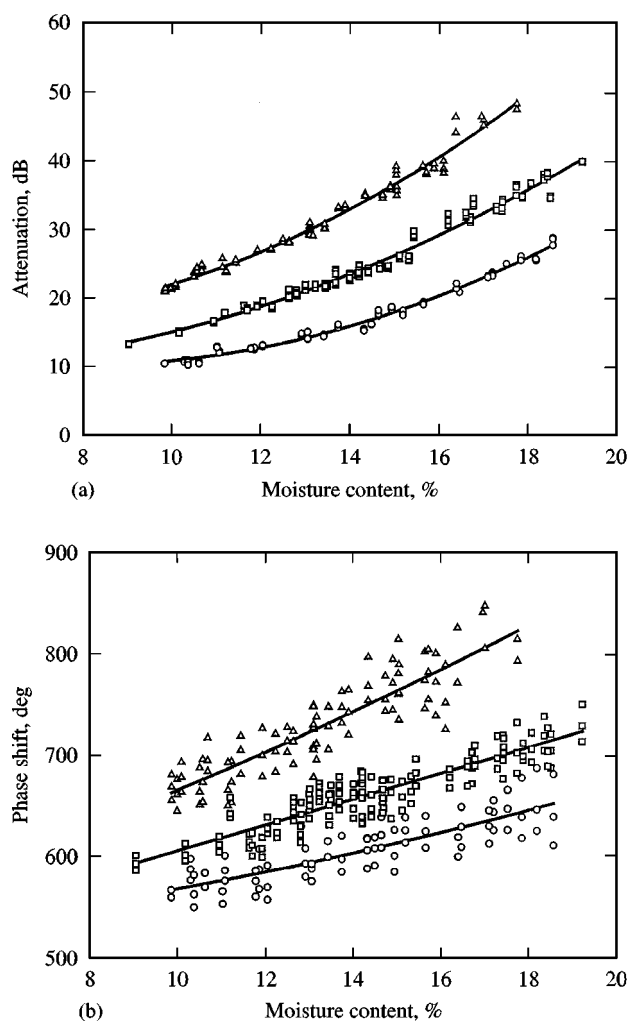


Fig. 2. Attenuation and phase shift as functions of moisture content for a layer of shelled maize at 15.2 GHz and three temperatures: \circ , 4°C ; \square , 24°C ; \triangle , 45°C

for all temperatures from 4 to 45°C , was divided into two equal subsets, a calibration set (even points) and a validation set (odd points). A list of some possible mathematical models for fitting the calibration data set is presented in Table 1. As an example for the procedure, three calibration equations of various degrees of complexity are presented below.

First, the calibration data set was fitted by appropriate regression analyses for the following equations (case a, Table 1):

$$A = 20.96 + 0.2914k + 0.4097T - 0.0565g, \quad r^2 = 0.9593$$

$$\phi = 39.7 + 2.8433k + 3.1853T + 0.3715g, \quad r^2 = 0.9408$$

where r^2 is the coefficient of determination. Following the procedure outlined above (Eqns (8)–(11)], the calibration

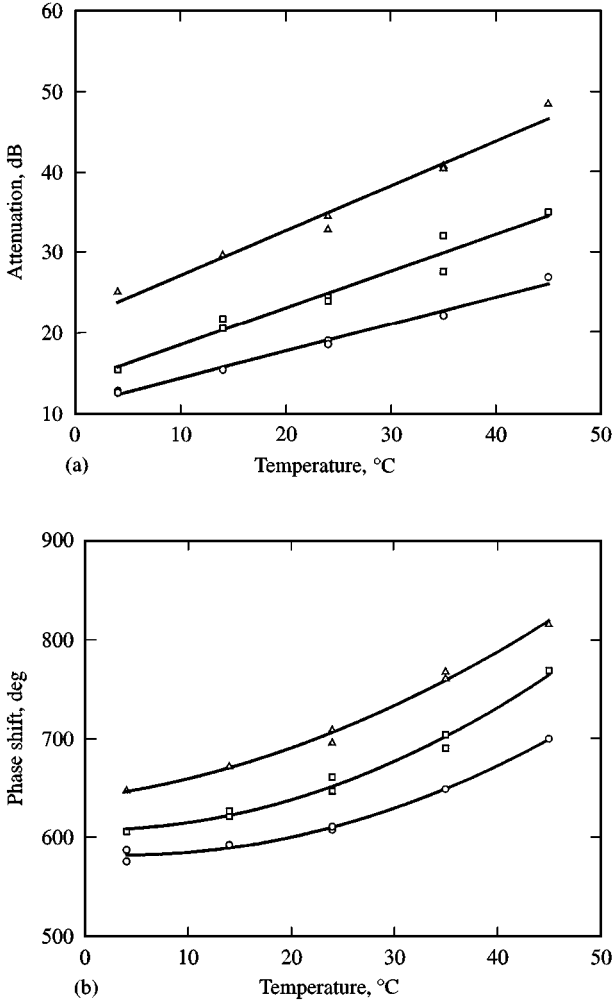


Fig. 3. Attenuation and phase shift for a layer of shelled maize as functions of temperature at 15.2 GHz and three moisture contents: \circ , 11.8% w.b.; \square , 14.5% w.b.; \triangle , 17.5% w.b.

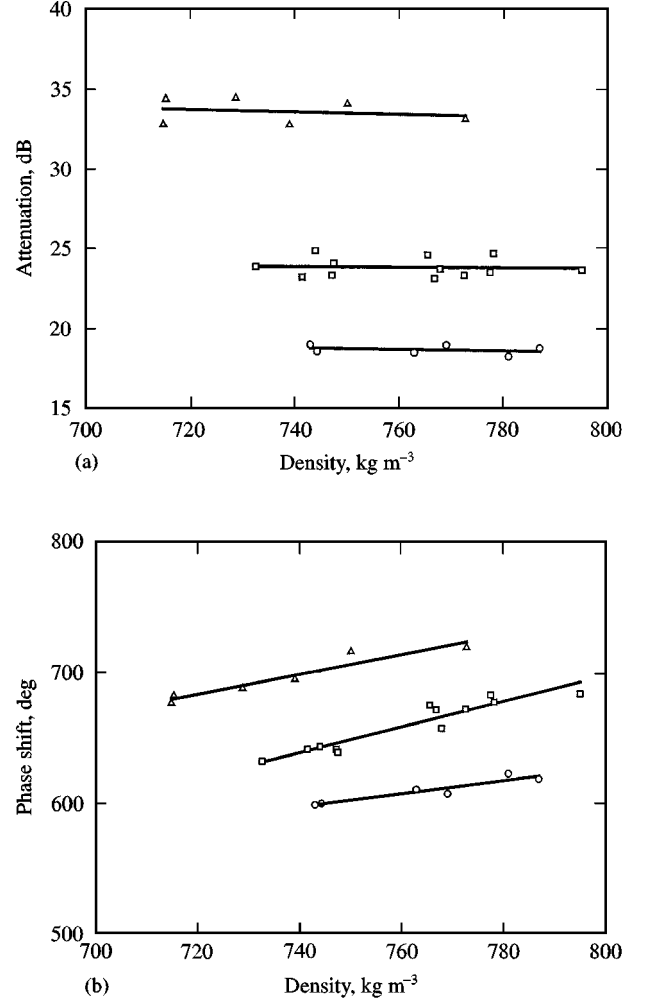


Fig. 4. Attenuation and phase shift as functions of grain bulk density for a layer of shelled maize at 15.2 GHz, 24°C, and three moisture contents: \circ , 11.8% w.b.; \square , 14.5% w.b.; \triangle , 17.5% w.b.

equations for moisture content and bulk density can be written as follows:

$$M = \frac{21.01\phi + 138.17A - 123.57T - 3730.4}{1.294\phi - 9.193A - 0.354T + 141.32} \quad (\%)$$

$$\rho = 1.294(\phi - 7.104A - 0.273T + 109.21) \quad (\text{kg/m}^3) \quad (13)$$

Next, the calibration data set was fitted by the following equations (case b, Table 1):

$$A = 32.744 + 0.1913k + 0.0039kT - 0.0585g, \quad r^2 = 0.9744$$

$$\phi = 130.7 + 2.069k + 0.0304kT + 0.3573g, \quad r^2 = 0.9567$$

which lead to the following calibration equations:

$$M = \frac{5.85\phi + 35.73A - 1935.65}{0.2498\phi - 1.712A + T(0.0304A + 0.0039\phi - 1.506) + 23.45} \quad (\%)$$

$\rho =$

$$\frac{0.2498\phi - 1.712A + T(0.0304A + 0.0039\phi - 1.506) + 23.45}{0.003172T + 0.1894} \quad (\text{kg/m}^3) \quad (14)$$

The third calibration equation can be developed by fitting the experiments to the following equations (case c, Table 1):

$$A = 40.237 + 0.000935k^2 + 0.00392kT - 0.05536g,$$

$$r^2 = 0.9795$$

$$\phi = 233.7 + 0.00974k^2 + 0.0306kT + 0.3628g$$

$$r^2 = 0.9591$$

Table 1
List of mathematical models for the experimental data for shelled maize

Attenuation models	r^2	Phase-shift models	r^2
$a_1 + a_2k$	0.5468	$b_1 + b_2k$	0.3383
$a_1 + a_2kT$	0.6026	$b_1 + b_2kT$	0.7736
$a_1 + a_2k^2T$	0.7987	$b_1 + b_2k^2T$	0.8943
$a_1 + a_2k + a_3kT$	0.9495	$b_1 + b_2k + b_3T$	0.9203
^(a) $a_1 + a_2k + a_3T + a_4g$	0.9593	$b_1 + b_2k^2 + b_3k^2T$	0.9298
$a_1 + a_2k^2T + a_3g$	0.9594	$b_1 + b_2k + b_3kT$	0.9378
^(b) $a_1 + a_2k + a_3kT + a_4g$	0.9744	$b_1 + b_2k^2 + b_3kT$	0.9396
$a_1 + a_2k + a_3kT + a_4g + a_5gT$	0.9747	^(a) $b_1 + b_2k + b_3T + b_4g$	0.9408
$a_1 + a_2k^2 + a_3k^2T + a_4g$	0.9757	^(b) $b_1 + b_2k + b_3kT + b_4g$	0.9567
^(c) $a_1 + a_2k^2 + a_3kT + a_4g$	0.9795	$b_1 + b_2k + b_3kT + b_4g + b_5gT$	0.9568
$a_1 + a_2k + a_3k^2 + a_4kT + a_5g$	0.9833	^(c) $b_1 + b_2k^2 + b_3kT + b_4g$	0.9591
$a_1 + a_2k + a_3k^2 + a_4kT + a_5g + a_6gT$	0.9840	$b_1 + b_2k^2 + b_3kT + b_4k^2T + b_5g$	0.9593

Note: Letters in parenthesis indicate models represented by Eqns (13), (14) and (15).

and solving them as before for:

$$k = -1.7737T + 569.2\sqrt{\Delta}$$
$$g = 1.0643\phi - 11.0865A - 0.01932T^2$$
$$+ 197.39 + 6.202T\sqrt{\Delta} \tag{15}$$

where $\Delta = (194.5\phi + 1275A + 9.71T^2 - 96750) \times 10^{-6}$ and calculating M and ρ from Eqn (2).

Validity of the calibration equations [Eqns (13)–(15)] was checked with the validation set of 259 data points not used for the development of the equations. Results of the computations performed for the validation data set were compared with oven moisture determinations. Performance statistics are listed in Table 2. The histogram presented in Fig. 5 shows the distribution of differences between oven moisture content determination and moisture content calculated from Eqn (15). The bias, \bar{e} , and the standard error of performance (SEP) were determined as

$$\bar{e} = \frac{1}{N} \sum_{i=1}^N e_i \quad \text{and} \quad \text{SEP} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (e_i - \bar{e})^2} \tag{16}$$

where $e_i = (M_{\text{oven}} - M_i)$, N is the number of samples, M_i is the moisture content predicted for the i th sample and M_{oven} is the moisture content determined for the same sample by the standard oven method. For results with Eqn (15), the mean difference (bias) was -0.023% moisture, while the standard deviation of differences (standard error of performance) with an average moisture content of 14% , was 0.449% moisture. Similar calculations performed for the maize bulk density were compared with the bulk density determined from the weight and volume of the sample. The distribution of differences in density for Eqn (15) is presented in Fig. 6. The bias and SEP for the same set of data as above, with an average bulk density of 765 kg/m^3 , were 0.33 and 14.19 kg/m^3 , respectively.

From Fig. 4, it may be observed that the attenuation introduced by a layer of shelled maize does not depend strongly upon the material density, which is contrary to results for other materials tested in the RF and microwave regions.¹ This indicates that the attenuation alone could be a valid measure of the moisture content. Several models relating A to M and T were considered and are

Table 2
Comparison of the precision of density-independent calibration equations

Frequency, GHz	Temperature, °C	Equation, origin*	Moisture content, %		Bulk density, kg m^{-3}	
			Bias	SEP*	Bias	SEP†
9.4	24	Ref. 4	0.135	0.287	− 3.6	12.83
15.2	4–45	^(a)	0.022	0.590	− 0.42	13.07
15.2	4–45	^(b)	− 0.021	0.496	0.41	13.57
15.2	4–45	^(c)	− 0.023	0.449	0.33	14.19
15.2	4–45	Eqn(17)	0.010	0.365	—	—

*Letters refer to Table 1 †Standard error performance.

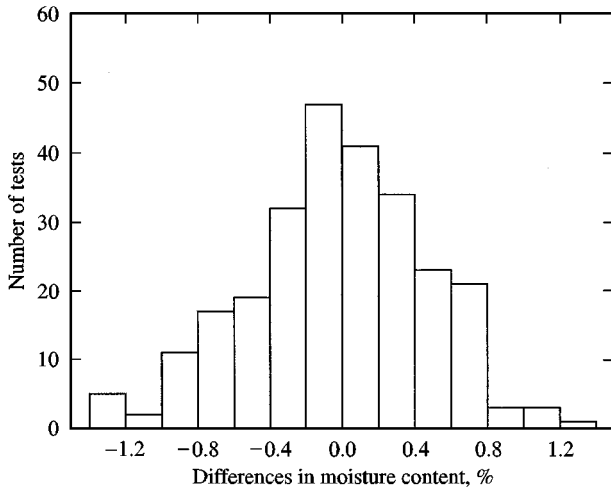


Fig. 5. Distribution of differences between oven moisture content determination and moisture content calculated for three lots of maize from calibration equation, Eqn (15), for 259 validation measurements at 15.2 GHz

listed in Table 3. The following equation, the last model listed in Table 3, was chosen for further consideration:

$$A = 13.144 + 0.03682MT - 1.6614M + 0.12269M^2 - 0.09323T, \quad r^2 = 0.9865$$

Solving for M ,

$$M = 4.07526 \left(B + \sqrt{B^2 + 0.49077(A - 13.144 + 0.09323T)} \right) (\%) \quad (17)$$

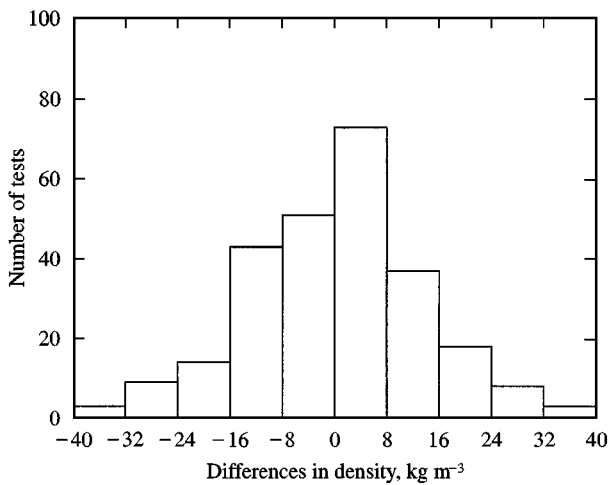


Fig. 6. Distribution of differences between measured maize bulk density and the density predicted from calibration equation, Eqn (15), for 259 validation measurements of three lots of corn at 15.2 GHz

Table 3
List of models for attenuation in a layer of shelled corn at 15.2 GHz

Attenuation model	r^2
$A = a_1 + a_2MT$	0.6442
$A = a_1 + a_2M^2T$	0.8540
$A = a_1 + a_2MT + a_3M$	0.9778
$A = a_1 + a_2MT + a_3M + a_4T$	0.9780
$A = a_1 + a_2M^2T + a_3M^2$	0.9786
$A = a_1 + a_2MT + a_3M^2$	0.9845
$A = a_1 + a_2MT + a_3M + a_4M^2$	0.9858
$A = a_1 + a_2MT + a_3M + a_4M^2 + a_5T$	0.9865

where $B = 1.6614 - 0.03682T$, and T is the material temperature in $^{\circ}\text{C}$. Validation of this calibration equation was performed in the same manner as described above for Eqns (13)–(15). The distribution of differences between oven moisture content and that predicted from the equation is presented in Fig. 7. The bias for 259 validation data points was 0.010% moisture and the SEP value was 0.365%.

5. Discussion

This paper describes a continuation of work reported previously⁴ in which the physical principles of the measuring method were explained in detail. In this work, however, a higher operating frequency was used, and

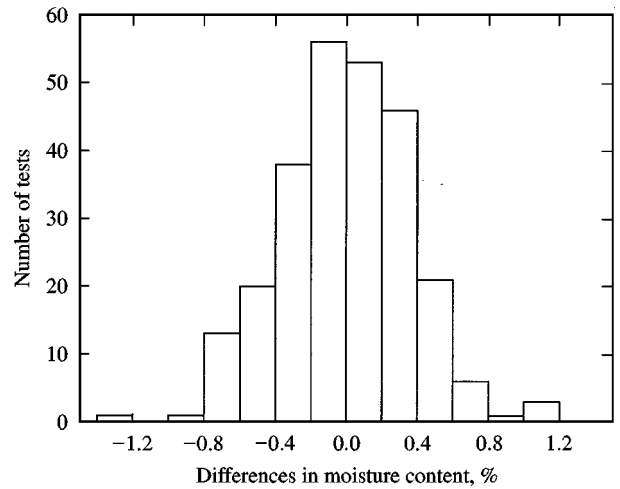


Fig. 7. Distribution of differences between oven moisture content determination and moisture content calculated for three lots of maize from calibration equation, Eqn (17), for 259 validation measurements at 15.2 GHz

grain was measured at various temperatures, allowing the development of calibration equations for temperature-compensated and density-independent moisture content determinations. There are several advantages of higher operating frequencies. First, dimensions of the waveguide components (transitions, horn antennas) are smaller at higher frequencies, which in the future could lead to smaller and more compact instruments. At higher frequencies, the grain layer thickness and distance between the antennas can be smaller. This could provide a better defined and smaller measuring space, which could be useful in determining spatial distribution of moisture in the material. However, at higher frequencies, scattering effects are more pronounced and the dynamic range of the attenuation measurements is reduced. This research, however, has shown that moisture determination by measurements with K-band frequencies (15.2 GHz) are feasible. The moisture content can be predicted, at the 95% confidence level, with an uncertainty less than 0.72% and the grain bulk density is given with an uncertainty of 25 kg/m³ for shelled maize of 9 to 19% w.b. moisture content at temperatures from 4 to 45°C. The error distribution (*Figs 5–7*) is very close to a normal distribution, indicating that the sign of the error is not related to the range of measured values and that the errors are of random character for both predicted variables.

There are essentially two mechanisms responsible for the energy loss in transmission through a material, as may be noted from Eqn (4). The principal one is the absorption indicated by the attenuation constant α (real part of the propagation constant), and the second can be composed of reflections, scattering and diffraction. In a layer of homogeneous material, reflections take place only at two, flat, limiting surfaces between air and the material, and the power dissipated in the layer can be determined with Eqn (5). In granular material, however, especially when sizes of particles become comparable with a significant fraction of the wavelength of the wave travelling through the material, reflections take place at interfaces between air and the particles. In this case, the transmission path of the wave through the layer of grain cannot be considered unique, because, inside the layer, multiple waves reflected from kernels of irregular size and non-uniform dimensions approach interfaces at various angles and are reflected and diffracted by them according to the rules of optics. Also the plane of wave polarization can be rotated during wave passage through the layer. Qualitative description of the energy loss requires complicated mathematics and most often contains limitations regarding size, shape and/or distribution of the scatterers (kernels) in space.^{8–10} However, no matter how complex the physical picture, the density effect on wave attenuation at 15.2 GHz in shelled maize is apparently minimal

(*Fig. 4*), thus permitting a high correlation between attenuation and moisture content. This feature has not been observed previously for any other granular or particulate materials measured at various microwave frequencies.

Use of attenuation alone provided a good measure of moisture content. With Eqn (17), moisture measurements are independent of grain bulk density and are compensated for temperature. The standard error of performance is lower than for the procedure including measurement of both attenuation and phase, and the only potential disadvantage is the lack of information for a bulk density determination. The question remains whether the observed density independence of the attenuation is a unique feature of the particular operating frequency or the frequency band. In an effort to answer this question, SEP values were calculated for several other frequencies in the K-band.⁶ The results of the calculation listed in Table 4 indicate that similar performance can be obtained at the other frequencies.

It may be noted in Table 2 that the more complex models have lower standard errors of performance for moisture content. However, the standard errors for the bulk density determination are similar. Because the cost of on-line, real-time computation is decreasing with the development of fast data processors, more complex and more accurate models can be considered for the calibration data. Table 2 also includes performance data for a previous model developed for data at 9.4 GHz and constant grain temperature.⁴ Comparisons show that the compensation for material temperature can be introduced into the calibration equation providing density-independent and temperature-compensated moisture and bulk density determinations.

No differences among the three maize hybrids were observed in the measured data. Thus, a calibration performed for shelled maize at these frequencies, where ionic conductivity of the material does not affect the measured variables, is likely to be valid for a wide range of maize. Other commodities, such as wheat, rapeseed and

Table 4
Frequency dependence of the SEP calculated from calibration equations corresponding to Eqn (17)

Frequency, GHz	Wavelength, cm	Moisture content, %		<i>r</i> ²
		Bias	SEP	
11.3	2.635	0.014	0.368	0.9873
13.3	2.254	0.012	0.372	0.9871
15.2	1.972	0.010	0.365	0.9865
16.8	1.784	0.010	0.379	0.9861

soybeans, may require separate calibrations. Although static grain samples were measured in the experiments described in the paper, the results should be applicable to dynamic measurements of flowing grain. The measurement arrangement shown in *Fig. 1* can be easily adapted for dynamic on-line measurements by providing flow of the material between the antennas. As contact between the measuring antennas and the material is not required for measurement of the microwave parameters, this may be a convenient, fast, accurate and nondestructive method of moisture content determination in flowing material. It can also be applied for many materials other than grain, such as powdered, granulated, or semiliquid materials.

6. Conclusions

Density-independent and temperature-compensated calibration equations can be developed for determining moisture content from attenuation and phase shift measurements at microwave frequencies in the K-band. Results show that moisture contents of shelled maize are determined with standard errors of performance less than 0.5% moisture content over normal bulk density ranges, moisture contents from 9 to 19%, wet basis, and temperatures ranging from 4 to 45°C.

With the same calibration data used for the moisture determination, grain bulk density can be determined from attenuation and phase measurements with a standard error of performance of 14 kg/m³ over the same range of moisture contents, temperatures, and bulk densities averaging 765 kg/m³.

At 15.2 GHz, attenuation data alone provided equal or better moisture determination than measurement of both attenuation and phase shift.

No differences were observed among three maize hybrids in the moisture contents and bulk densities determined from the K-band microwave measurements.

Based on the measurements and calibrations developed for shelled maize samples, and the convenient features of such free-space microwave measurements, the microwave techniques offer promise for the development of reliable grain moisture meters for on-line moisture monitoring applications.

Acknowledgements

The authors are deeply grateful to David Funk, Chief, Inspection Systems Engineering Branch, Grain Inspection, Packers and Stockyards Administration, Kansas City, Missouri, for thoughtful reading of the original manuscript and for noting the possibility for predicting moisture content in corn with attenuation only. This approach, the oldest historically, and recently abandoned for more modern and complicated solutions, proved effective in the case discussed in the paper. Support of the research by Campbell, Scientific, Inc., is also gratefully acknowledged.

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